9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

Spin-orbit interaction in AlGaAs/GaAs p-type quantum wells — a possible explanation of the 'metal-insulator' transition observed in two-dimensional hole systems

L. E. Golub† and S. Pedersen‡
† Ioffe Physico-Technical Institute, St Petersburg, Russia
‡ Microtechnology Center at Chalmers MC2, Department of Microelectronics and Nanoscience, Chalmers University of Technology and Göteborg University, S-412 96, Göteborg, Sweden

Abstract. We have performed a calculation of the temperature dependence of the weak-localization correction to resistance in a AlGaAs/GaAs p-type quantum well. In such systems, where the spin-orbit coupling by far dominates the energy dispersion, we find that the spin relaxation time becomes comparable with the estimated value of the phase coherence time at sufficiently low temperatures and low hole densities. We wish to suggest this crossover between these different relaxation times as a possible explanation of the experimentally observed 'metal-insulator' transition in two-dimensional hole systems.

In a series of recent experiments an anomalous temperature dependence of the resistivity has been observed in a wide range of two-dimensional systems — for an extensive overview see [1] and references therein. These results have been interpreted as evidence for the existence of a so-called metal-insulator transition in two-dimensional systems | a conclusion considered by far the most as controversial.

In this work we theoretically address one specific system | namely the 200 Å wide AlGaAs/GaAs p-type quantum well which has been experimentally studied in [2, 3]. Several other similar studies has been reported in the literature [4, 5, 6, 7], but for clarity we will primarily focus on the work done by Simmons and co-workers.

The results of these experiments can be summarized as follows: A transition between an isolating phase at low hole densities and a metallic phase at high hole densities is observed at a critically hole density $p_c \approx 5 \times 10^{14}\,\mathrm{m}^{-2}$ | by isolating (metallic) phase is meant that the resistivity increases (decreases) with decreasing temperature. Furthermore the investigation of the magnetoresistance lead to the following observations: (1) The phase coherence time τ_φ extracted from weak localization measurement agrees well with the theoretical estimates [8], (2) The effect of hole-hole interacting on the resistivity was found to be of the same size as the weak localization correction, and in agreement with the theory for weak hole-hole interaction [9], and (3) No weak anti-localization was observed. Observation (1) and (2) was independent on which side of 'metal-isolator' transition the measurement was performed and hence lead to the surprising conclusion that the hole-hole interactions properly not are responsible for the observed transition even though $r_s > 1$.

In this letter we take the above conclusion as starting point for our examination, hence we neglect hole-hole interaction and try to explain the observed behavior within weak-localization theory, which is reasonable to assume valid since the experiment where performed in the regime where $\tau_\varphi > \tau_{\mathrm{tr}}$; τ_{tr} being the transport relaxation time.

The reason why no weak anti-localization was observed is most likely, that in these structures the weak anti-localization is expected to be very small since $k_F a/\pi \ll 1$ [10] (k_F is the Fermi wavevector, a is the quantum well width), and furthermore in the performed

experiment the magnetic field was stepped with an increment of ~ 50 Gauss which would be much to gross to resolve the effect (In a similar hole system the whole weak anti-localization regime was found within ± 30 Gauss [11]).

Contrary to what is commonly believed, a metallic phase can in principle occur in two dimensions. Such a 'metal-insulator' transition is as a fact expected to occur in non-interacting systems with strong spin-orbit coupling [12, 13]. In real systems this so-called anti-localization is expected to be suppressed due to hole-hole interaction, which is supposed to dominate if interactions are present. However for the system in question, one of the surprising experimental findings were, that the effect of hole-hole interaction was comparable with the interference effects even though $r_s > 1$.

For a non-interacting two-dimensional system where $\tau_\varphi \sim \tau_s > \tau_{tr}$; τ_s being the spin relaxation time, the weak localization approximation is valid and the temperature dependence of the conductivity is given by [12]

$$\sigma(T) - \sigma_0 = \begin{cases} \frac{e^2}{\pi h} \ln(\tau_\varphi/\tau_s), & \tau_s/\tau_\varphi < 1 \\ -\frac{e^2}{\pi h} \ln(\tau_\varphi/\tau_{tr}), & \tau_s/\tau_\varphi > 1, \end{cases} \tag{1}$$

where $\sigma_0 = pe^2\tau_{tr}/m$ is the temperature independent Drude conductivity (m is the effective mass in the bottom of the first size-quantized hole subband). Hence the sign of the weak-localization correction is given by the ratio between the strength of the spin coherence and the phase coherence τ_s/τ_φ. If the spin relaxation is strong $\tau_s/\tau_\varphi < 1$ the plus sign is valid. On the other hand if the spin relaxation is weak the minus sign is valid and the well known weak-localization result is retained [8]. Hence we see that by changing the ratio τ_s/τ_φ it is possible to induce a transition like the one observed in the experiments.

Spin relaxation of holes is caused by spin-orbit interaction, therefore it is governed by the hole density, p. Changing p, one can transfer the system from one to the other case (1). In real p-type two-dimensional systems, hole spin relaxation is anisotropic and, hence, it is described by two characteristic times, $\tau_\parallel$ and $\tau_\perp$. The conductivity correction has the form [10]

$$\sigma(T) - \sigma_0 = \frac{e^2}{\pi h}\left[2\ln\left(\frac{\tau_{tr}}{\tau_\varphi} + \frac{\tau_{tr}}{\tau_\parallel}\right) + \ln\left(\frac{\tau_{tr}}{\tau_\varphi} + \frac{\tau_{tr}}{\tau_\perp}\right) - \ln\left(\frac{\tau_{tr}}{\tau_\varphi}\right)\right]. \tag{2}$$

In the lowest order in pa^2, we obtained [10]

$$\frac{\tau_{tr}}{\tau_\parallel} = L_\parallel (pa^2)^2, \qquad \frac{\tau_{tr}}{\tau_\perp} = L_\perp (pa^2)^3. \tag{3}$$

For a GaAs/AlGaAs quantum well, $L_\parallel = 2.7 \cdot 10^{-4}$, $L_\perp = 0.12$ [14].

The phase coherence time τ_φ is assumed to be caused by hole-hole interaction and, hence, it is determined by both temperature, T, and density:

$$\frac{\tau_{tr}}{\tau_\varphi} = \frac{mk_B T}{2\pi\hbar^2 p} \ln\left(\frac{2\pi\hbar p \tau_{tr}}{m}\right). \tag{4}$$

The system is insulating at high temperatures and low densities, when $\tau_\varphi < \tau_\parallel, \tau_\perp$, and it is metallic in the opposite case of low T and high p, when spin-orbit interaction is more effective than dephasing.

The transition between these two states of matter, the 'metal-insulator' transition (MIT) takes place at $\partial\Delta\sigma/\partial T = 0$. From (2) follows that the curve $\sigma(T)$ has zero slope at

$$\frac{1}{\tau_\varphi} = \sqrt{\frac{1}{(4\tau_\perp)^2} + \frac{1}{2\tau_\parallel\tau_\perp}} - \frac{1}{4\tau_\perp}. \tag{5}$$

This condition defines the dependence of the critical density, p_c, on temperature or, vice versa, the MIT-temperature, T_c, as a function of p. From (3) follows that $1/\tau_\parallel \gg 1/\tau_\perp$ at $pa^2 \ll L_\parallel/L_\perp$. Therefore according to (5) the MIT occurs at $\tau_{tr}/\tau_\varphi \approx \tau_{tr}/\sqrt{2\tau_\parallel \tau_\perp}$, i.e.

$$T_c(p) = \frac{2\pi\hbar^2}{mk_B \ln(2\pi\hbar p\tau_{tr}/m)}\sqrt{\frac{L_\parallel L_\perp}{2}}p^{7/2}a^5\,, \qquad pa^2 \ll L_\parallel/L_\perp\,. \tag{6}$$

For $pa^2 \gg L_\parallel/L_\perp$, $1/\tau_\parallel \ll 1/\tau_\perp$ and the p-dependence of T_c is given by $1/\tau_\varphi \approx 1/\tau_\parallel$, i.e.

$$T_c(p) = \frac{2\pi\hbar^2}{mk_B \ln(2\pi\hbar p\tau_{tr}/m)}L_\parallel p^3 a^4\,, \qquad pa^2 \gg L_\parallel/L_\perp\,. \tag{7}$$

The expressions (6,7) give $T_c \sim 10^{-2}$ K for the structure parameters of the experiments [2, 3] ($a = 200$ Å, $m = 0.3m_0$). This is about an order of magnitude smaller than the experimental temperature of MIT. This discrepance could be due to under-estimation of the spin-orbit interaction strength in the lowest-order calculations leading to very small values of $L_\perp$ and, especially, $L_\parallel$. Besides, the higher degrees of p could be important in the expressions for the spin relaxation rates (3). The corresponding calculation is performed taking into account heavy-light hole mixing in a quantum well in all orders in wavevector and will be published elsewhere.

Acknowledgements

L.E.G. acknowledges the Russian Foundation of Basic Research, projects 00-02-17011 and 00-02-16894, and the Russian State Programme "Physics of Solid State Nanostructures" for financial support.

References

[1] E. Abrahams, S. V. Kravchenko and M. P. Sarachik, cond-mat/0006055.
[2] M. Y. Simmons, A. R. Hamiliton, M. Pepper, E. H. Linfield, P. D. Rose and D. A. Ritchie, *Phys. Rev. Lett.* **84**, 2489 (2000).
[3] M. Y. Simmons, A. R. Hamiliton, M. Pepper, E. H. Linfield, P. D. Rose, D. A. Ritchie, A. K. Savchenko and T. G. Griffiths, *Phys. Rev. Lett.* **80**, 1292 (1998).
[4] A. P. Mills,Jr., A. P. Ramirez, L. N. Pfeiffer and K. W. West, *Phys. Rev. Lett.* **83**, 2805 (1999).
[5] V. Senz, T. Heinzel, T. Ihn, K. Ensslin, G. Dehlinger, D. Grützmacher and U. Gennser, *Phys. Rev. B* **61**, R5082 (2000).
[6] Y. Hanein, U. Meirav, D. Shahar, C. C. Li, D. C. Tsui and H. Shtrikman, *Phys. Rev. Lett.* **80**, 1288 (1998).
[7] J. Yoon, C. C. Li, D. Shahar, D. C. Tsui and M. Shayegan, *Phys. Rev. Lett.* **82**, 1744 (1999).
[8] B. L. Altschuler, A. G. Aronov and D. E. Khmel'nitskii, *J. Phys. C* **15**, 7367 (1982).
[9] B. L. Altschuler, A. G. Aronov and P. A. Lee, *Phys. Rev. Lett.* **44**, 1288 (1980).
[10] N. S. Avierkiev, L. E. Golub and G. E. Pikus, *JETP* **86**, 780 (1998).
[11] S. Pedersen, C. B. Sørensen, A. K. Kristensen, P. E. Lindelof, L. E. Golub and N. S. Averkiev, *Phys. Rev. B* **60**, 4880 (1999).
[12] B. L. Altschuler, A. G. Aronov, D. E. Khmelnitskii and A. I. Larkin, *Quantum Theory of Solids*, ed I. M. Lifshits (MIR Publishers, Moscow, 1983).
[13] B. L. Altschuler, D. L. Maslov and V. M. Pudalov, cond-mat/0003032.
[14] N. S. Averkiev, L. E. Golub and G. E. Pikus. *Solid State Commun.* **107** 757 (1998).